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Research article

Changes in mechanical properties of wood pellets during artificial degradation in a laboratory environment



Shalini Graham^a, Ibrahim Ogunfayo^a, Matthew R. Hall^{a,b}, Colin Snape^a, Will Quick^c, Susan Weatherstone^c, Carol Eastwick^{a,*}

^a Faculty of Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

^b British Geological Survey, Environmental Science Centre, Keyworth, Nottingham NG12 5GG, UK

^c Uniper Technologies Ltd. (formerly E.ON Technologies), Technology Centre, Ratcliffe on Soar, Nottingham NG11 0EE, UK

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ABSTRACT

In stockpiles exposed to high relative humidity (RH) and rainfall, woody biomass pellets lose structural integrity, often assumed to be due to the uptake of moisture from the environment. In this study three different types of biomass pellet were artificially degraded in a laboratory environment under controlled exposure to RH (10% and 90% RH) and temperature (range of 10 to 30 °C). White, torrefied and steam-exploded wood pellets were investigated. Daily shear tests were conducted with durability and moisture content measured. The exposure of all three pellet types to high RH coupled with elevated temperatures caused a substantial decrease of shear modulus with values of 50% to 92% decrease compared to fresh pellets after 4 days of exposure.

The steam exploded pellets saw the lowest drop in mechanical durability (5%) but saw the largest decrease in shear modulus, whilst the white wood pellets disintegrated in situ after 4 days. In contrast storage at 10% RH did not cause any observable degradation, with mechanical behaviour of steam exploded and torrefied pellets showing an improvement. This paper presents both testing methodology as well as clear indication of the behaviour of three woody biomass pellets on exposure to high relative humidity.

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1. Introduction

As power generators continue their search for alternative energy sources to coal, biomass remains a promising carbon-based renewable fuel [1]. Biomass fuel dedicated combustion and co-firing with coal are being utilised and optimised to improve fuel flexibility in power-plants and reduce greenhouse gas (GHG) emissions. Densified biomass fuels such as pellets are preferred as they provide better economic viability for transport, storage and handling [2]. One of the challenges facing the energy industry is how to store the large quantities of biomass fuel required for thermal power plants [3]. During a study on the long-term impact of weathering on the mechanical and chemical properties of biomass fuels during storage [4], it was noted that the mechanical degradation of the pellets resulting from moisture intake was more substantial than the chemical degradation. Whilst there have been several recent publications relating to storage impacts on the mechanical properties of wood pellets, these have investigated long term impact [5,6] or impact of pre-treatment [7,8]. The systematic investigation of short term storage humidity and temperature on mechanical properties on biomass wood pellets has not been studied. Therefore a study on the

effects of relative humidity (RH) and surrounding temperature on the structural changes in wood pellets was carried out using laboratory investigations where the impact of continuous exposure to high RH at ambient and elevated temperatures on the mechanical properties of three different wood pellets (white wood, torrefied and steam exploded) was undertaken.

Previous work has been carried out on biomass fuels in related areas such as of sourcing and procurement [9], logistics of transport [10], effects of storage and handling on physical properties [11–13], conveying and milling operations [14], combustion efficiency [2] and emissions and ash control [15,16]. More relevant to this investigation is the work of Lehtikangas [5] examining changes in the properties of nine different types of pelletised fuel during storage when exposed to heat and humidity/water vapour over a period of five months. No significant changes were observed in the bulk density, individual pellet density, ash content and calorific value. The most noticeable impacts were pellet length, 25 to 50% drop, and durability, measured as percentage of fines <3 mm after tumbling, with an increase of 300% in the worst case. Pellet length reduction as a result of storage was also reported by [6] in their work on canola straw pellets.

The impact of thermal treatment on the properties of pellets has also been investigated [7,8] with a reduction of moisture uptake reported with increasing severity of thermal treatment. Authors also noted

* Corresponding author.

E-mail address: Carol.Eastwick@nottingham.ac.uk (C. Eastwick).

changes in strength and hardness although these were dependent on the treatment type and severity. Peng et al. [7] manufactured pellets from sawdust samples torrefied at a temperature range of 240 to 340 °C and compacted at a range of temperatures and pressures, whilst Lam et al. [8] investigated the steam explosion of Douglas fir at four different treatment severities (at 200 and 220 °C and for 5 and 10 min at each temperature).

Peng et al. [7] measured moisture uptake in an environmental chamber set at 30 °C and 90% relative humidity. For an increase in the pellet torrefaction temperature from 240 to 340 °C the moisture uptake over 24 h decreased from 14 to 8% and the pellet hardness decreased by as much as 90%. A decrease in the moisture and volatile contents could have contributed to a weakening of interfacial forces, adhesion and cohesion forces, solid bridges and interlocking forces. However Lam et al. [8] noted that steam treatment led to an increase in pellet elasticity, higher mechanical strength and increased moisture sorption resistance for most conditions.

As previously stated, the long term study [4] by the authors identified there may be a link between pellet degradation behaviour in outdoor/non fully enclosed storage where high relative humidity levels (90%) and temperatures above 20 °C were encountered, and this is the hypothesis investigated within this paper. By carrying out a small scale study simultaneously investigating exposure to combinations of relative humidity and temperature at short time scales, and measuring the extent of mechanical degradation (pellet durability and three point flexural shear modulus), a more systematic analysis of the impact of relative humidity and temperature was achieved. These tests simulated pellet storage in outdoor or exposed (for example an open barn) environments with sensitivity tests at lower humidity included for comparative purposes. In the long term storage trials [4] completed between April 2011 and December 2012, the relative humidity and ambient temperature were measured and recorded continuously for a period of twenty months, with variations in relative humidity from 65 to 95%, the summer months averaging 10–15% higher than in the winter months. The relative humidity trend over the storage period showed higher levels of humidity for sustained periods (90% and above for 16 consecutive weeks) compared to past years [17]. Ambient temperature matched UK year on year averages (measured at Waddington weather station, Met Office UK) [17] very closely, and ranged from –10 to 30 °C.

2. Material and methods

Two different laboratory storage environments were used in this work. In the first, wood pellets were enclosed in sealed containers and subjected to uncontrolled high relative humidity for several days; and in the second pellets were tested in an environmental chamber at controlled temperatures and relative humidity for varying time periods. The first method was trialled to establish whether simple testing would provide sufficient indicative trends to allow a low cost and quick method to be utilised in the biomass transport and storage industry in assessing the resistance of pellets to moisture uptake and mechanical degradation in outdoor/not enclosed storage scenarios. The second test in the environmental chamber provided a more robust test with controlled parameters to verify the results of the simple container test and therefore validate the method for simple low cost testing. The three pellets types investigated included a white wood pellet manufactured from de-barked virgin softwood, a torrefied pellet manufactured from a mixture of softwood and hardwood and a steam exploded pellets also manufactured from a mixture of softwood and hardwood. Two properties used to assess the mechanical strength of wood pellets were pellet durability [18] and shear modulus [3] under three point flexural testing. Durability measures the pellet's resistance to breakage during handling/motion according to the test stated in BS EN ISO 17831:1 [19] and the three point flexural shear represents the pellet's resistance to crack formation when a force is applied [4]. Typical

Table 1

Typical dimensions of each pellet type before storage tests.

Biomass pellet	Diameter (mm)	Length (mm)
Untreated white wood	6.00 ± 0.20	21.60 ± 2.00
Steam exploded	6.30 ± 0.10	18.00 ± 1.90
Torrefied	8.00 ± 0.10	15.70 ± 0.60

dimensions of the three pellet types utilised during these tests are summarised in Table 1.

2.1. Artificial degradation experiments in a sealed container

2.1.1. High humidity (ambient temperature)

For each pellet type, a high humidity environment at ambient temperature was generated by pouring 1 l of tap water into a sealed container kept at an average temperature of 20 °C. A metallic mesh 100–150 mm above the water surface held a mass of 250 g of pellets at the start of testing. Each day a sample of 15 pellets was removed for mechanical testing, these were randomly selected. A type-T thermocouple (silicone type) connected to a temperature data logger was positioned to measure in-situ pellet temperature. In addition, a Lascar EL-USB-2+ humidity data logger (Lascar Electronics Ltd., Salisbury, UK) was secured to the inside of the container lid to monitor relative humidity levels. The container was sealed (air-tight) during the trial to maintain a high level of in-situ humidity (Fig. 1 – not drawn to scale).

The temperature was recorded at a frequency of 30 s, whilst the humidity was recorded every 10 s, with readings being downloaded every 24 h. The mean and range (variation) of each 24 h period was determined. The mean daily temperature was 20 °C with a variation of ±0.9 °C as the room temperature was managed. The relative humidity initially was at a value of 70% RH (the background relative humidity level in the room) rising rapidly to an average of 95% RH with a daily variation of ±1% RH. The test lasted 17 days at which point severe pellet degradation had occurred and shear testing was no longer possible.

2.1.2. High humidity (elevated temperature)

A similar setup as in Section 2.1.1 was used. However the 1 l of water in the bucket was introduced at an elevated temperature of 60 °C. Each morning, the cooled water (20 °C) in the bucket was replaced by fresh hot water at 60 °C. This was to investigate the effect of a combination of higher temperatures and relative humidity on pellet degradation and the impact of a changing temperature regime (exaggerated day and night variations seen in the long term storage trial) on the pellets. The buckets were sealed and positioned in an insulating box. As in Section 2.1.1, temperature was recorded every 30 s and humidity every 10 s. As expected there was a large daily temperature variation; 60 °C in the morning with the temperature gradually decreasing to 20 °C by the evening. Relative humidity varied with the temperature profile seeing a range in values from 70 to 91% RH across the day. As there was a wide variation of temperature and relative humidity experienced by the pellets in these tests, follow on tests employing the environmental chamber sustained realistic higher temperature and relative humidity (Section 2.2). Storage at elevated temperatures only lasted 7 days due to the increased degradation rate seen by the pellets, making mechanical testing increasingly impractical with some pellets unable to be tested after 4 days.

2.2. Environmental chamber experiments

In the experiments in the enclosed containers described in Section 2.1, pellets were exposed to uncontrolled temperature and humidity variations. The variations in both temperature and humidity made it difficult to draw accurate conclusions about the impact of each separately. Therefore, an environmental chamber TAS LT CL 600 Series 3 [20] (TAS Ltd., West Sussex, UK) was used to enable the

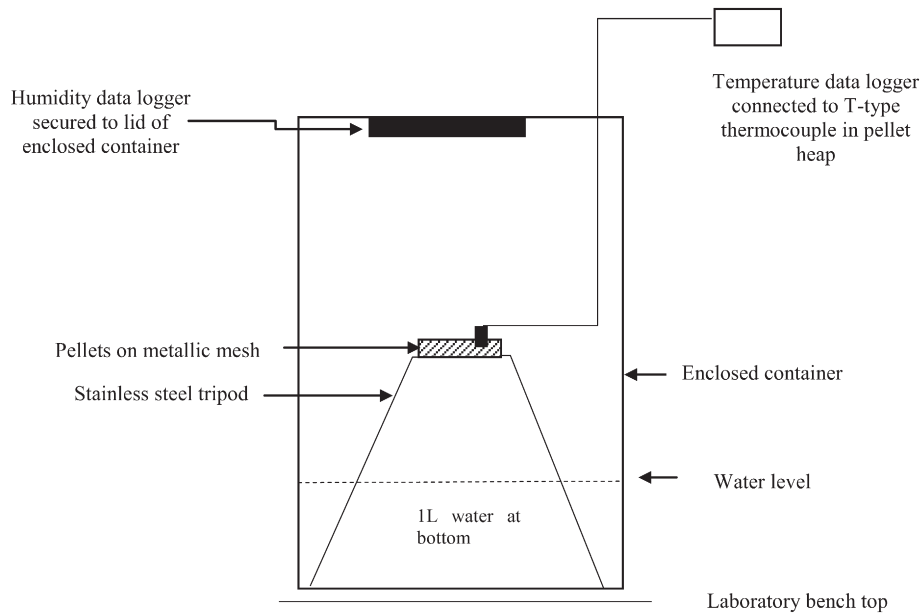


Fig. 1. Experimental setup for artificial degradation of pellets in enclosed containers.

temperature and relative humidity to be set and controlled throughout the testing period (Table 2). A matrix of high relative humidity 90% RH and low relative humidity 10% RH combined with temperatures ranging from 10 to 30 °C was investigated. The environmental chamber provides continuous control of the relative humidity to $\pm 3\%$ RH and the temperature to ± 1 °C. Approximately 100–150 g of each pellet type were evenly placed in one layer on small-sized trays (280 mm \times 220 mm) and placed into the environmental chamber compartment.

Initial tests were scheduled for 3 days but from an analysis of results it was clear that degradation occurred faster than expected within the first day and subsequent tests were limited to shorter time periods with additional sampling points introduced earlier in the test period. For the 90% RH/30 °C combination, daily sampling and mechanical testing took place. For the 90% RH/20 °C combination two additional sampling points were introduced on the first day of testing after 1.5 and 4.5 h.

2.3. Inter laminar shear/flexural test

On a daily basis fifteen pellets were removed randomly from each experiment and five pellets were randomly picked and used for the shear test. A shear test using the methodology described in [21] was conducted on the pellets. The shear test was performed on an Instron mechanical tester based on a 3-point flexural test setup similar to ASTM D143–09, which are standard test methods for small clear specimens of timber. This has been superseded by ASTM D143 14 [22]. The material used in the standard is raw wood of dimensions 50 \times 50 mm, very different to processed pelletised wood. However in this study the focus is to measure the extent of degradation over time rather than a

direct comparison to a standard, with the observed differences between the shear moduli of the fresh and degraded pellets appreciable.

For this test, pellets were picked with a length of 18 mm (± 1 mm) to achieve a length to diameter ratio of <2.5 in order to prevent possible errors during shearing and to maintain a level of uniformity in the shear pattern.

The lower contact probe has two circular contact points (5 mm diameter) with a span of 10.2 mm between the centres of the two contact bases. The force is applied from another probe attached to the load cell of 5 kN, and with an extension ramp rate of 1 mm/min. For each pellet type, five tests were carried out and the standard deviation calculated. Flexural load-extension profile plots were generated for each test and the shear modulus calculated automatically.

2.4. Durability test

Mechanical durability tests were conducted on fresh pellets and on degraded pellets at the end of the storage period. The pellet mechanical durability was conducted at E.ON Technologies, using a Dural II durability tester. For each of the two degradation experiments, 100 g of pellets was placed in the tester and rotated at a speed of 1600 rpm for 30 s. The sample was then sieved at 4.75 mm. The durability of the pellets was calculated as the weight percentage in the oversize fraction. As a pellet sample size of 250 g was used initially for the enclosed container tests, with pellets removed daily for testing, the final mass available allowed for only one durability test to be completed for each pellet type. However triplicates were carried out on fresh samples to establish the repeatability of the process and yielded a sample variation of 1–4%.

$$\text{Durability} = \frac{(M_{\text{sample}}) \times 100}{M_{\text{total}}} \quad (1)$$

where M_{sample} = Mass of sample larger than 4.75 mm, M_{total} = Total mass of sample.

In the work of [4], the Dural II tester is compared with the tumbler in BS EN-15210 which has now been superseded by [19]. The then standard method was a less forceful and slower test with a larger sample size of 500 g and it therefore yielded higher durability values than the Dural II tester. The comparison tests described in [4] demonstrated that the Dural II tester showed larger changes in durability (for instance instead of a 20% change, a 60% change is seen between fresh and very

Table 2
Relative humidity and temperature settings for environmental chamber tests.

Parameter combination	Relative humidity (RH) %	Temperature °C	Exposure duration days
90% RH/10 °C	90	10	1
90% RH/20 °C	90	20	3
90% RH/30 °C	90	30	3
10% RH/20 °C	10	20	4
10% RH/30 °C	10	30	1

degraded pellets) providing more detail on the impact of degradation as the spread of values seen is greater, meaning it is possible to highlight the different stages of degradation.

3. Results and discussion

3.1. Artificial degradation experiments in a sealed container

3.1.1. Changes in physical appearance of pellets

From visual inspection, the steam exploded pellets appeared to have been less impacted by the humidity tests than the other two types of pellets. Fig. 2a–e shows a selection of photographs and electron zoom microscopy images of the steam exploded pellets; whilst Figs. 3 and 4 show the torrefied and white wood pellets respectively before and after the tests at elevated temperature.

At the end of the high humidity at ambient temperature (20 °C) tests (Fig. 2b and d), the steam exploded pellets were completely wet and a sticky brownish swelling was observed on the surface of the pellets due to moisture uptake (Fig. 2d). In addition to pellet wetness and

swelling the pellets at the end of the high humidity tests at elevated temperature also showed signs of cracks and surface degradation (Fig. 2e). It is hypothesised that the higher cyclic temperature range (20–60 °C) results in pellet expansion and contraction, which coupled with the swelling due to moisture uptake, results in crack formation and propagation as layers within pellets move. The same behaviour was observed by [4] when pellets were stored outdoor in uncovered storage during the warmer summer months.

For the torrefied pellets crack formation was noticeable on the pellets after the humidity tests at ambient temperature. At elevated temperature tests (Section 2.1.2) degradation was even more severe with multiple cracks on each pellet (Fig. 3b). The torrefied pellets were manufactured through a dry torrefaction process which has been proved to destroy the natural binding capacity of the biomass and hence a reduction in pellet mechanical strength [8] is seen. In contrast to dry torrefaction, hydrothermal treatment using steam was reported to be an effective pre-treatment for woody biomass with improved mechanical strength and moisture adsorption resistance of pellets reported [23].

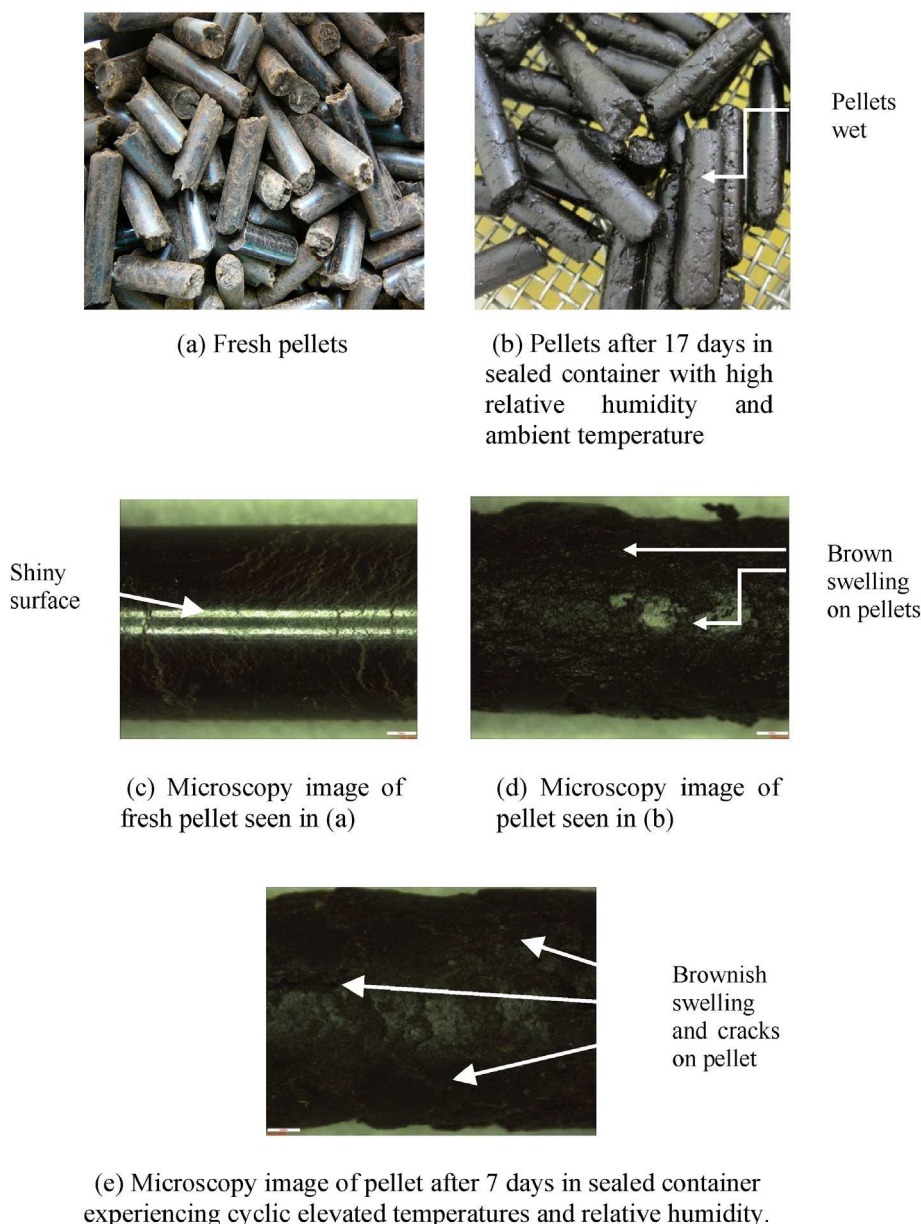


Fig. 2. (a–e) Fresh steam exploded pellets and pellets after storage at high relative humidity at ambient and elevated temperature tests.

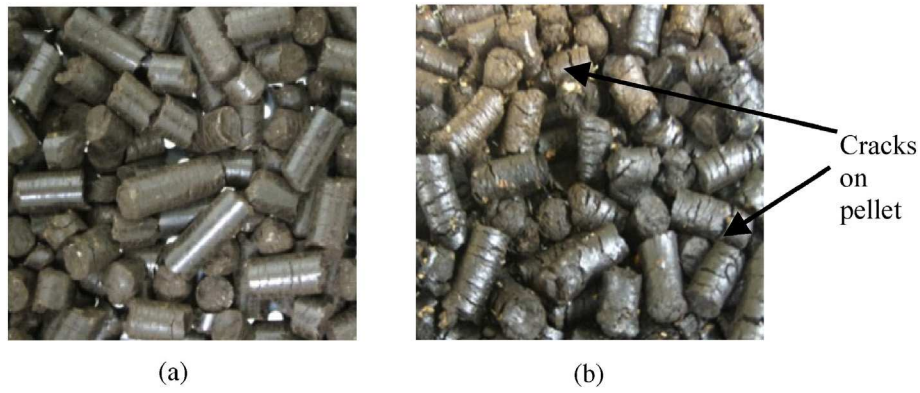


Fig. 3. Photographs of fresh torrefied pellets (a) and pellets after testing at elevated temperature and relative humidity (b).

During the humidity test at ambient temperature, crack formation and propagation to the core of the white wood pellets were imminent; and when elevated temperature was combined with high humidity pellet disintegration occurred as early as the second day of testing with pellet breaking up (Fig. 4b). This indicates that white wood pellets have a high intolerance to moisture uptake when exposed to high relative humidity. According to the work of [23,24] pellets made from steam exploded wood had a breaking strength 1.4 to 3.3 times larger than the strength of the pellet made from untreated wood with the same pelletisation condition. It was postulated that a modified restructure of lignin after steam explosion contributes to the increase in breaking strength.

3.1.2. Shear tests results

Fig. 5 shows the average shear modulus against numbers of days of storage for the three types of pellets in the tests at ambient temperature and elevated temperature in sealed containers (Sections 2.1.1 and 2.1.2). The sample variation of five replicates is illustrated by the error bars in each of the graphs. The variation in results arises due to the inhomogeneous nature of biomass pellets and is expected [4], this being the reason for multiple repeats of mechanical tests.

From Fig. 5 it is clear that there are discernible trends for the steam exploded pellets and correlations are extracted, although the significant variation in results mean that these should be considered as indicative correlations rather than definitive. For the steam exploded pellets a correlation for the tests at ambient temperature yields

$$\text{Shear modulus (MPa)} = -45.32 \ln(\text{days in storage}) + 162.35 \quad (2)$$

with a value of $R^2 = 0.9133$ can be obtained.

Whilst for the steam exploded pellets for tests at elevated temperature a correlation of

$$\text{Shear modulus (MPa)} = -110 \ln(\text{days in storage}) + 167.84 \quad (3)$$

with a value $R^2 = 0.9332$ can be obtained.

Whilst these correlations should be viewed as indicative trends only, as the data is sparse and with significant variation present, it is clear that the tests with elevated cyclic temperature are seeing an appreciably faster degradation in strength. For the steam exploded pellets the decrease is such that the shear modulus at day four has decreased by 92% compared to the original value of the fresh pellet.

In contrast the white wood pellets show a shallow degradation behaviour for the ambient temperature tests described in Section 2.1.1 as shown in Fig. 5 with the highlighted correlation of

$$\text{Shear modulus (MPa)} = -12.67 \ln(\text{days in storage}) + 39.89 \quad (4)$$

with an $R^2 = 0.9481$.

The pellets exposed to higher temperature and relative humidity (test as described in Section 2.1.2) show a decrease in value within 3 days of 76%, degradation after 4 days meaning that they were unable to be tested (see Fig. 4b). The torrefied pellets similarly showed a decrease in value, 50% decrease after 4 days for ambient temperature tests, whilst at the higher temperature a 56% decrease was seen after 4 days, there are no significantly significant correlations discernible for the torrefied pellets.

The resulting shear modulus at the end of the testing period reflects the starting shear modulus of the fresh pellets. The fresh and degraded steam exploded pellets had higher shear moduli than both the torrefied and white wood pellets; this shows that steam explosion does result in an enhancement in pellet stiffness. In their work on the mechanical and compositional characteristics of Douglas fir pellets, [8] reported that the improvement in hardness and dimensional stability of steam treated

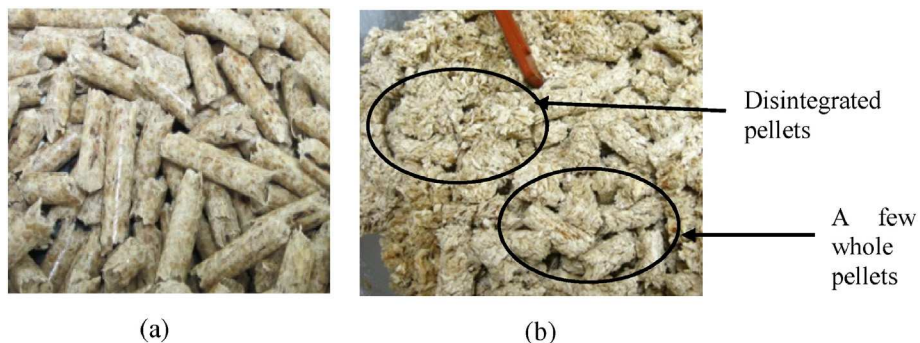


Fig. 4. Fresh white wood pellets (a) and pellets after humidity at elevated temperature test (b) showing the disintegration of pellets in situ on completion of test.

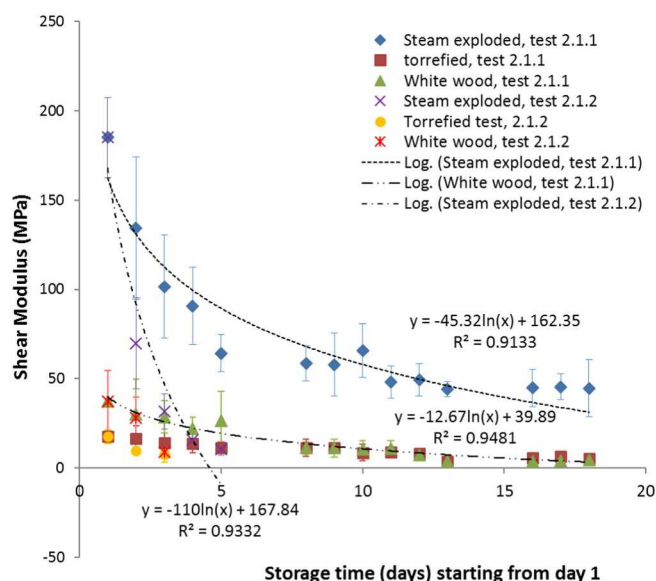


Fig. 5. Shear modulus against days in artificial degradation storage experiments in a sealed container as described in Sections 2.1.1 and 2.1.2.

pellets can be explained by the binding role of mono-sugars released from Douglas fir during hydrothermal treatment. Another contributing factor would be the modified restructure of lignin which improves mechanical strength as discussed in Section 3.1.1. However it is clear from these tests that the steam exploded pellets are impacted by high relative humidity with appreciable degradation in shear modulus seen.

3.1.3. Durability and moisture test results

The durability and the moisture content of the fresh pellets and the degraded pellets at the end of the testing periods were also measured. According to the IS CEN/Technical Specification 14961:2005 Solid biofuels – Fuel specifications and classes [25], a pellet durability of as high as 97% is required and a moisture content of 8–10%. The results of the humidity at ambient and elevated temperature tests are summarized in Fig. 6 and Table 3.

As the pellets absorb moisture upon continuous exposure to humidity swelling occurs resulting in cracks as seen in Figs. 2–4. The

combination of elevated temperature and a humid environment accelerates the moisture intake (third column in Table 3). These changes in structure make the pellet more susceptible to breakage during the durability test and hence also during handling and conveying. The steam exploded pellets exhibited higher durability compared to the other two pellet types, retaining 94% and 84% of their initial durability at the end of the humidity tests at ambient and elevated temperatures respectively. The torrefied pellets retained 29% and 7% of their initial durability at the end of the humidity tests at ambient and elevated temperatures respectively, whilst the equivalent durabilities for the white wood pellets were 9% and 0.5% of the initial durability of the fresh pellets.

A key observation is the much higher durability of the fresh steam exploded and white wood pellets compared to the torrefied pellets. The torrefaction of the wood may have caused it to become completely dried and to lose its tenacious and fibrous structure, hence increasing its brittleness [26]. Furthermore, as discussed in Sections 3.1.1 and 3.1.2, the higher mechanical strength of the steam exploded pellets can be attributed to a modified restructure of the lignin and the binding role of mono-sugars which are released during hydrothermal treatment.

In the long term storage study carried out by the lead author [4], the steam exploded pellets stored in an open barn (covered storage with exposure to ambient humidity and temperature) showed little change in durability whereas the white wood pellets exposed in the same barn were severely degraded.

3.2. Environmental chamber experiments

Table 2 in Section 2.2 shows the different temperature and humidity combinations used in the environmental chamber tests. The low relative humidity of 10% was investigated combined with a temperature of 20 and 30 °C whereas at 90% humidity, three temperatures were investigated (10, 20, 30 °C). This is because the tests in the enclosed containers clearly showed the impact of high humidity on pellet degradation. Figs. 7–9 show the shear modulus against time in storage of the steam exploded, torrefied and white wood pellets respectively, when subjected to various combinations of humidity and temperature. As for Fig. 5, the mean shear modulus is shown together with the range of data from the five repeats as error bars. For all three pellets, the largest drop in shear modulus occurs after the first day.

It can be seen in Fig. 7 that the exposure of steam exploded pellets to the highest temperature and relative humidity combination 90% RH/

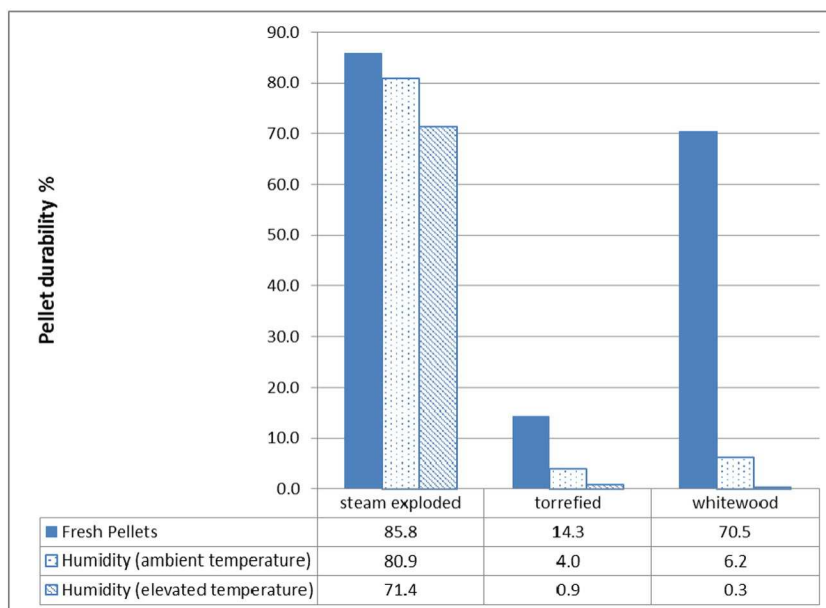


Fig. 6. Durability of biomass pellets before and after artificial degradation experiments in a sealed container.

Table 3

Moisture content (wet basis) of three pellet types before and after artificial degradation experiments in a sealed container using oven drying method (105 °C for 24 h).

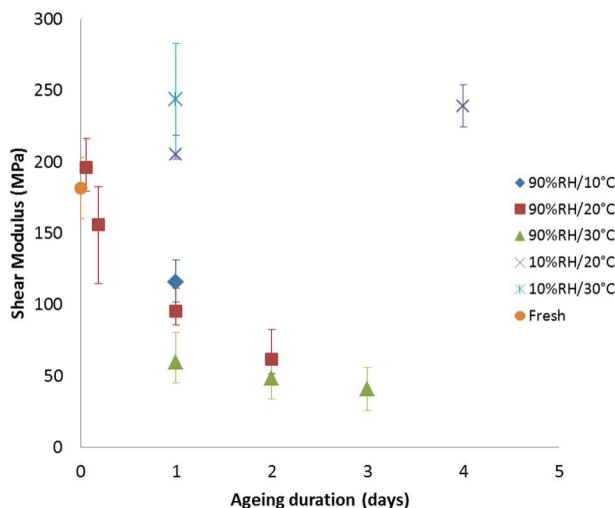
Pellet type	Fresh pellets	After humidity tests at ambient temp		After humidity tests at elevated temp
	Moisture % (wet basis)	Moisture % (wet basis)		Moisture % (wet basis)
Steam exploded	5.7	17.4		24.8
Torrefied	7.07	15.2		29.2
White wood	8.5	20.3		22.3

30 °C caused the largest decrease in shear modulus compared to the other relative humidity/temperature pairs. Compared to the fresh pellet the shear modulus decreased by 67% after 1 day and 77% after the 3 days. At a high relative humidity of 90%, the extent of degradation after one day at 30 °C is almost three times higher than at 10 °C.

The trends in Fig. 7 are similar to those seen in Fig. 5 with a substantial decrease in shear modulus seen on exposure to high humidity that becomes more pronounced as temperature is increased. Whilst there is insufficient data to draw meaningful correlations, the data has similar magnitude versus time in the environmental chamber compared to the tests carried out using the sealed containers shown in Fig. 5.

When the humidity is dropped to 10%, which is lower than ambient within the room, the shear modulus increases which further confirms the impact of humidity on the pellets. At the low relative humidity of 10%, an increase in temperature from 20 °C to 30 °C did not result in an appreciable difference in the rate of pellet degradation. This reinforces the findings from the results from the sealed containers reported in Section 3.1.2 that continuous exposure to high humidity is a major factor affecting the decrease in pellet integrity during storage and handling.

With reference to Fig. 8, the results for the torrefied pellets show similar trends to Fig. 5 with a relatively smaller change in the absolute shear modulus compared to the steam exploded cases shown in Fig. 7. From Fig. 8, at 90% RH/20 °C the shear modulus dropped to 45% compared to the fresh pellet value by day 2, whilst the pellets exposed to 90% RH/30 °C fell to 60% after day 3. Similarly to the steam exploded pellets exposed to a low humidity of 10% shown in Fig. 7, the shear modulus of the torrefied pellets increases (Fig. 8), interestingly the variation seen across the repeats also increases. Comparing the shear modulus against days exposed to humidity in both Figs. 5 and 8, the magnitudes agree as well as the trends. This is further evidence that the simple sealed container tests are showing both trend and magnitude of the impact of humidity onto pellets shear modulus.

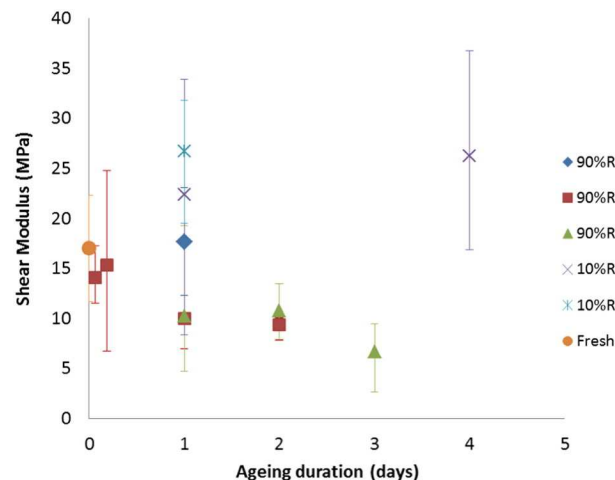
**Fig. 7.** Shear modulus against days in environmental chamber for steam exploded pellets at various humidity-temperature combinations.

As observed for the torrefied and steam exploded pellets, high humidity had an impact on the white wood pellets (Fig. 9) with the elevated temperature increasing the rate of degradation. It is also interesting to note the increase in variation across repeats seen for day 3 90% RH/30 °C with the lowest value dropping by over 95% of the fresh pellet shear modulus. The results at the low humidity of 10% do not show a discernible trend within the variation seen across the repeats. The results in Fig. 9 show similar trends and magnitudes to the results in Fig. 5.

The results from the tests in the environment chamber, which were undertaken at controlled and repeatable conditions, complement the results from the artificial degradation experiments in a sealed container drawing out similar trends. As the data for the environmental chamber is sparse, correlations have not been extracted from this data. However it is clear from both sets of tests that the steam exploded pellets, despite having the highest initial shear modulus, are severely impacted by the relative humidity and temperature of storage. Whilst the white wood pellets were so degraded by elevated temperature and humidity that they disintegrated. These results bear out observations in the field of the long term study [4] where pellets stored outdoors were observed to reach similar degraded states after periods of sustained high humidity and temperature. Although the trends and correlations observed are not directly applicable to large scale storage, nor were they designed to be, they do draw out the importance of the local climate for storage of both raw and pre-treated wood pellets and provide a simple testing methodology to establish a pellets susceptibility to humidity levels. So allowing industry to clarify whether controlled indoor storage is required for a pellet type depending on local conditions.

4. Conclusions

The exposure of steam exploded, torrefied and white wood pellets to high humidity increases their moisture content and reduces pellet shear modulus (stiffness) as well as pellet durability. When humidity is coupled with high temperature, the degradation rate is more severe

**Fig. 8.** Shear modulus against days in environmental chamber for torrefied pellets at various humidity-temperature combinations.

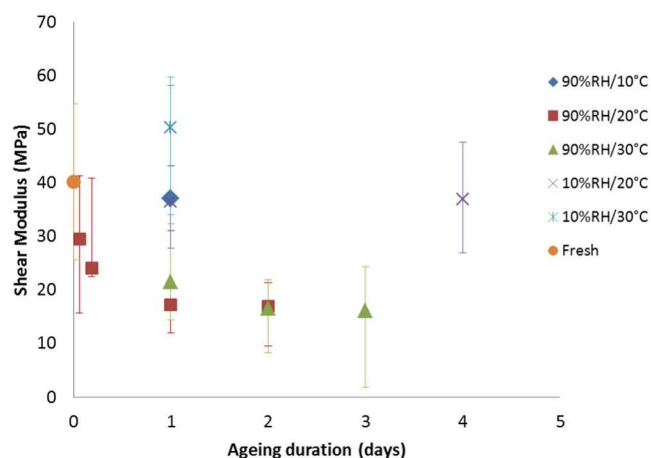


Fig. 9. Shear modulus against days in environmental chamber for white wood pellets at various humidity-temperature combinations.

and occurs faster. Temperature, when not coupled with high humidity did not discernibly impact the pellets mechanical strength.

The trends seen in enclosed container tests are validated by the environmental chamber testing with the same behaviours observed, indicating that the lower cost container tests would provide a good trend behaviour analysis for assessing the impact of moisture on pelletised biomass strength and durability. For the three pellet types, the degradation was most severe at a combination of high temperature and high humidity, at 30 °C and 90% RH respectively, for steam exploded pellets this led to a drop of between 77 and 92% within 4 days whilst the white wood pellets became so degraded they could not be tested. Storage at low humidity at 10% RH (20 °C and 30 °C) results in an increase in the shear modulus of the steam exploded and torrefied pellets.

The steam exploded biomass pellets maintained a higher mechanical durability at the end of the humidity tests at both ambient and elevated temperatures compared to the other pellet types. These findings confirm the trends seen in the long term storage of biomass pellets investigated by the lead author where the steam exploded pellets stored in an open barn showed high resistance to mechanical degradation. On the other hand, both the torrefied and white wood pellets are very susceptible to mechanical degradation upon exposure to high RH and temperature and should be stored in enclosed storage.

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